Constraining new physics with high-multiplicy : UHECR as a probe of new physics

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based on arXiv:1806.03063[hep-ph] with Yongsoo Jho

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motivation

- No New physics has been found at the LHC

$$\Lambda_{NP} \geq \mathrm{TeV}$$

- We can go beyond the collider energy using UHECR

$$E_{\mathrm{CR}} > 10^8 \mathrm{GeV} \Rightarrow E_{CM} = \sqrt{2E_{CR}M} > 10\ \mathrm{TeV}$$

- So, we may probe new physics appearing at high scale by CR!

$$E_{\mathrm{CM}} > \Lambda_{NP}$$

Seen in atmosphere!

- CR > 10^8 GeV fiercely bombing the Earth
- They interact with nucleons in atmosphere
- Producing multiple ‘high-multiplicity events’
- That may be seen at the ‘detectors’ … TA, Pierre Auger are our main target in this study. (IceCube will come as a sequel soon)

What new physics?

$$\Lambda_{NP} \sim 10 \text{ TeV}$$

- We don't know actually where NP would show up but…
  - '**Electroweak sphaleron**' scale ~10 TeV (a classical field configuration of SU(2) symmetry linking different vacuum states **within the SM**)
  - **Microscopic blackhole** is a robust prediction of <u>low-scale gravity scenarios</u> with warped or large extra dimensions, ~10 TeV

Sphaleron process

dictated by symmetry

$\Delta L = -3, \Delta B = -3$

$\mu^+ + \bar{\nu}_\tau$

$N(u) + \nu_e \to L + Q$ (+**EW bosons**)

$\bar{t} + 2\bar{b} + 2\bar{c} + \bar{s} + \bar{u} + \bar{d}$

nucleon in atmosphere

UHECR Neutrino

"sphaleron scale"

$E_{\rm sph} \approx 10\,\mathrm{TeV}$

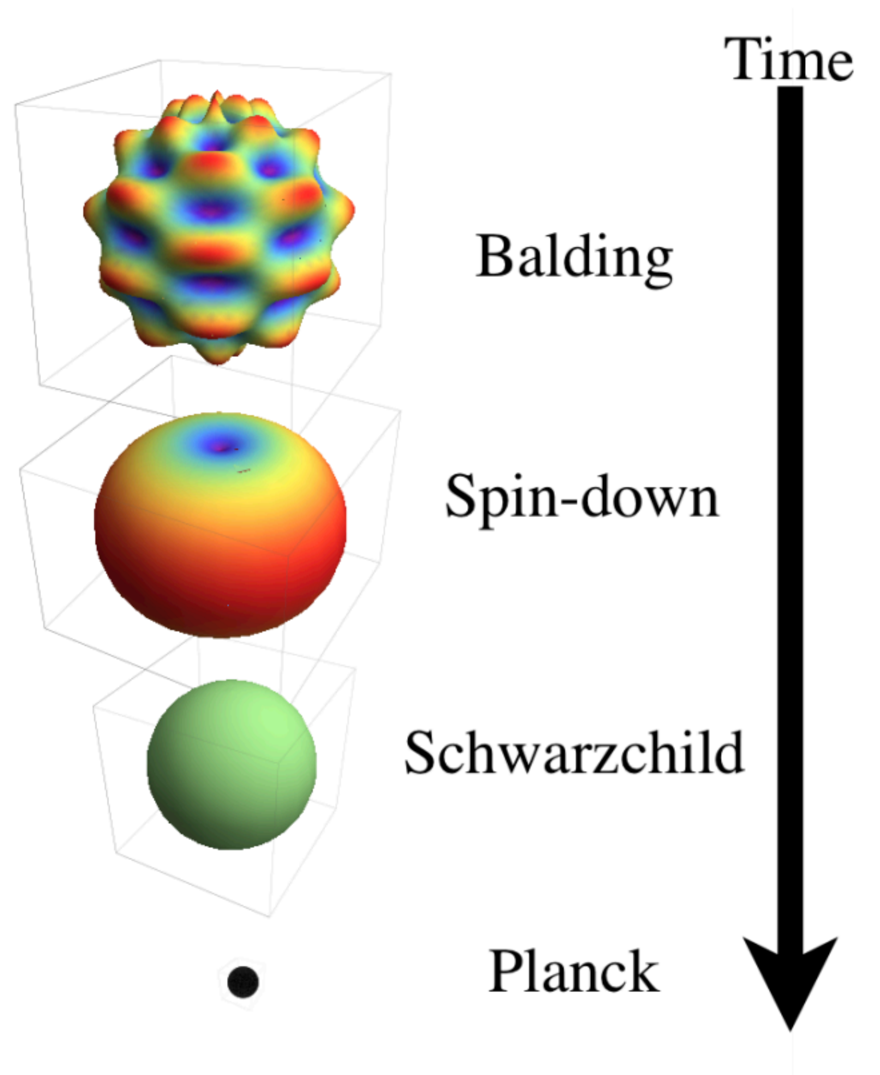
How often does this happen?

$$\hat{\sigma}_{ij\to \mathrm{EWSph}}(E_{\rm CM}) \simeq \frac{p}{m_W^2}\theta(E_{\rm CM}/E_{\rm sph})$$

@ parton level

H.Tye & Wang, PRD(2015, 2017)
J. Ellis & Sakurai, JHEP(2016)

Blackhole process via Hawking radiation



‘greybody factors’
Ida, Oda, SCP, PRD (2003, 2005, 2006)
SCP, Prog.Part.Nucl.Phys. 67 (2012) 617-650

How often does this happen?

$$\hat{\sigma}_{ij\to \mathrm{BH}}(E_{\mathrm{CM}}) \approx \pi \left(G_D E_{\mathrm{CM}}\right)^{\frac{2}{D-3}}$$

@ parton level

$$G_D = \frac{1}{M_D^{D-2}} \sim \frac{1}{\mathrm{TeV}^{\mathrm{D}-2}}$$

“TeV scale of gravity” in ADD or RS models

Common feature: sizable cross section >O(10)TeV

- Cross section becomes large at around E_{cm}~10 TeV

PDF

Nucleon's mass

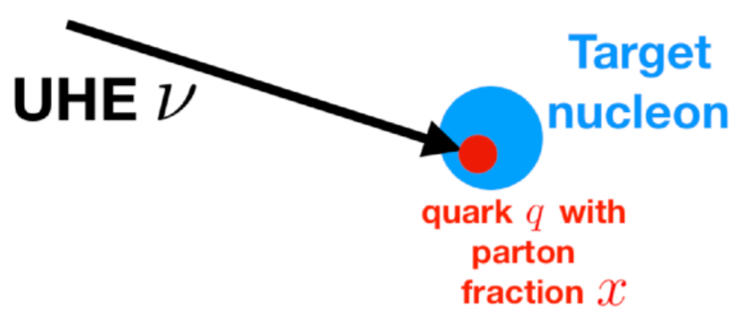
$$\sigma(E_\nu) = \sum_i \int dx f_{i/N}(x, q^2)\hat{\sigma}(\hat{s} = 2mE_\nu x) \sim 1/\mathrm{TeV}^2$$

CR-energy $E_{CM} > 10$ TeV

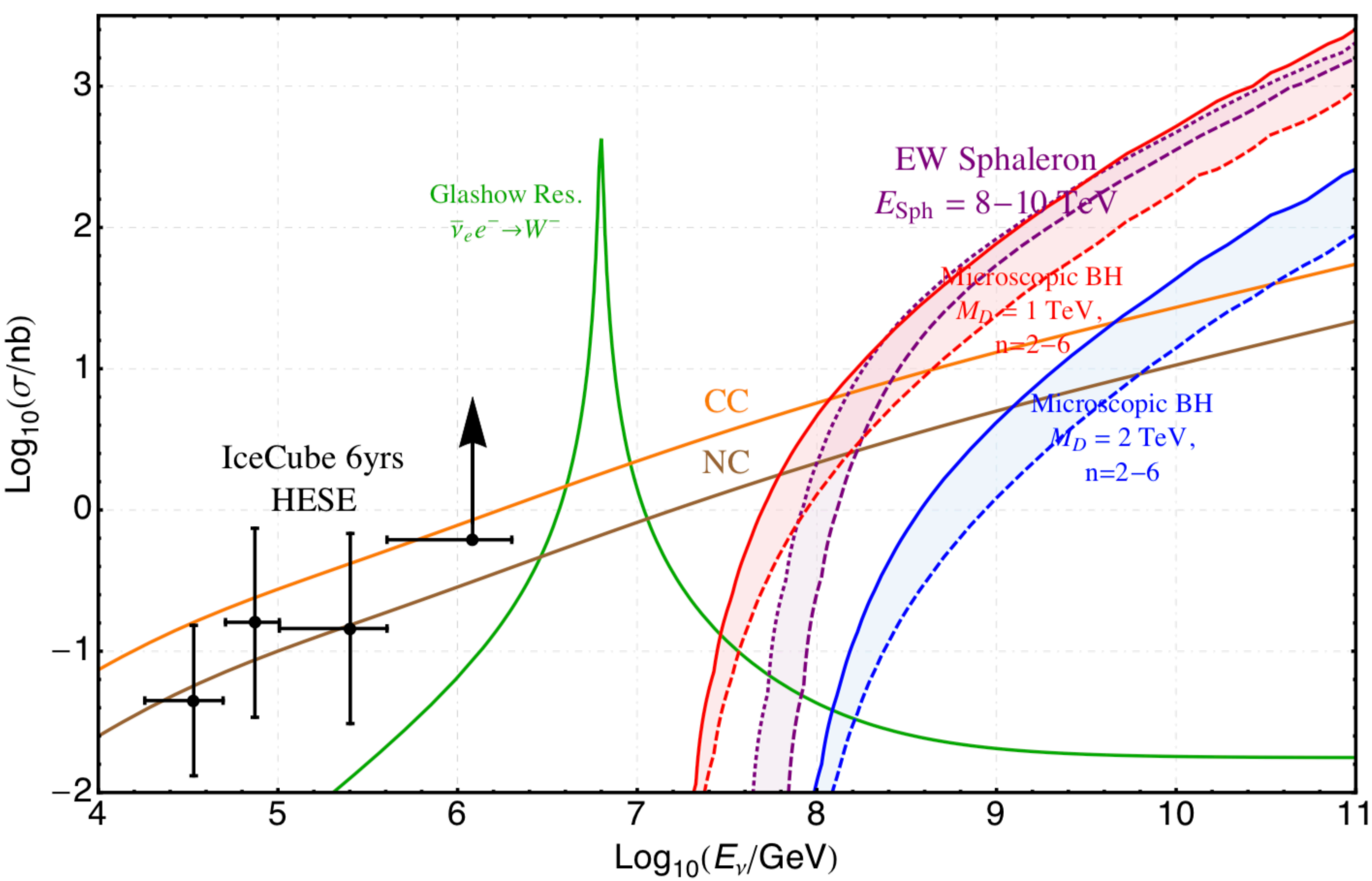
parton level x-section (NP)

fraction of energy of parton(i) in Nucleon

$$E_\nu \sim \mathcal{O}(10^{17} - 10^{21})\ \mathrm{eV}$$



N-nu cross sections



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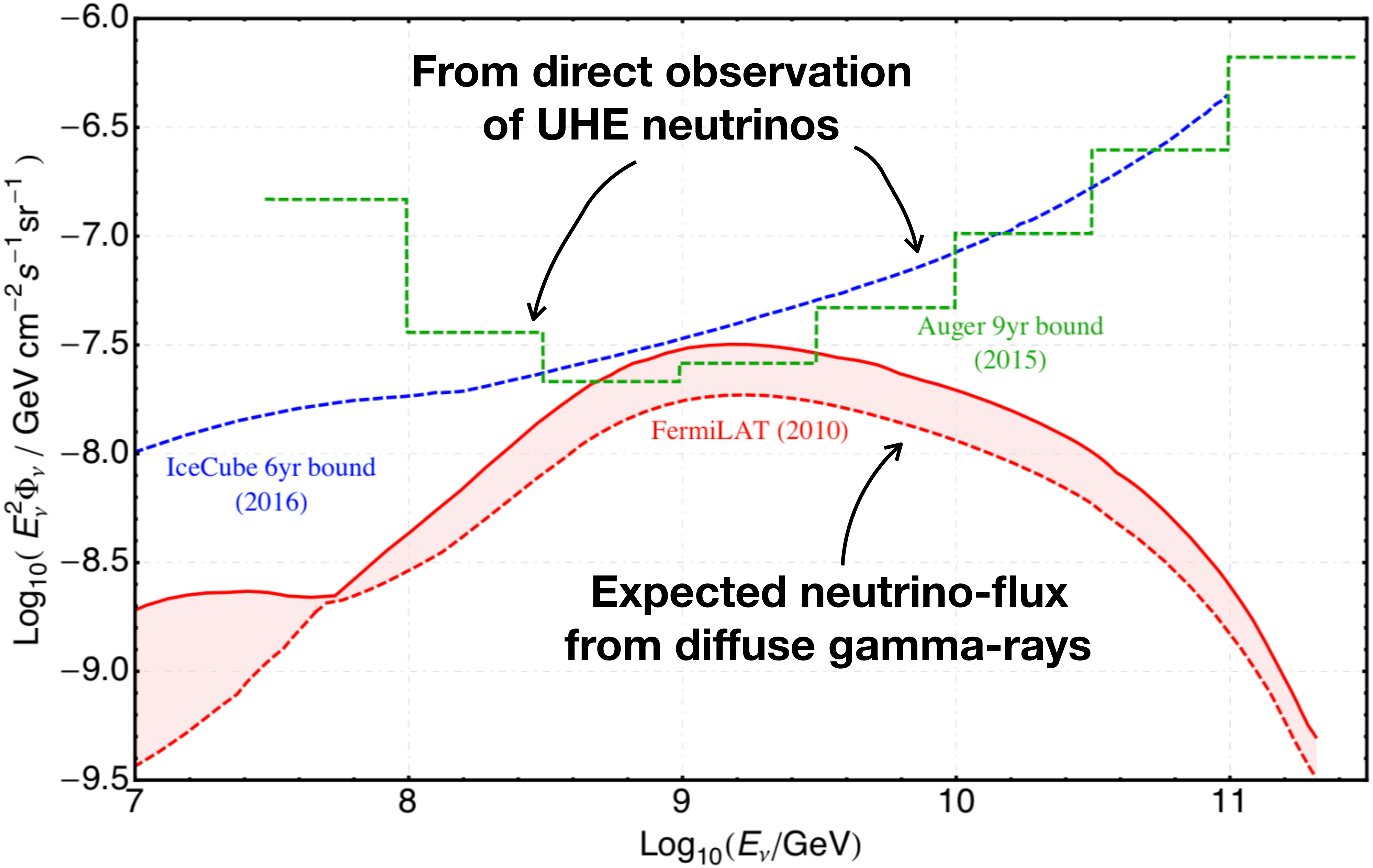
UHECR Neutrino flux



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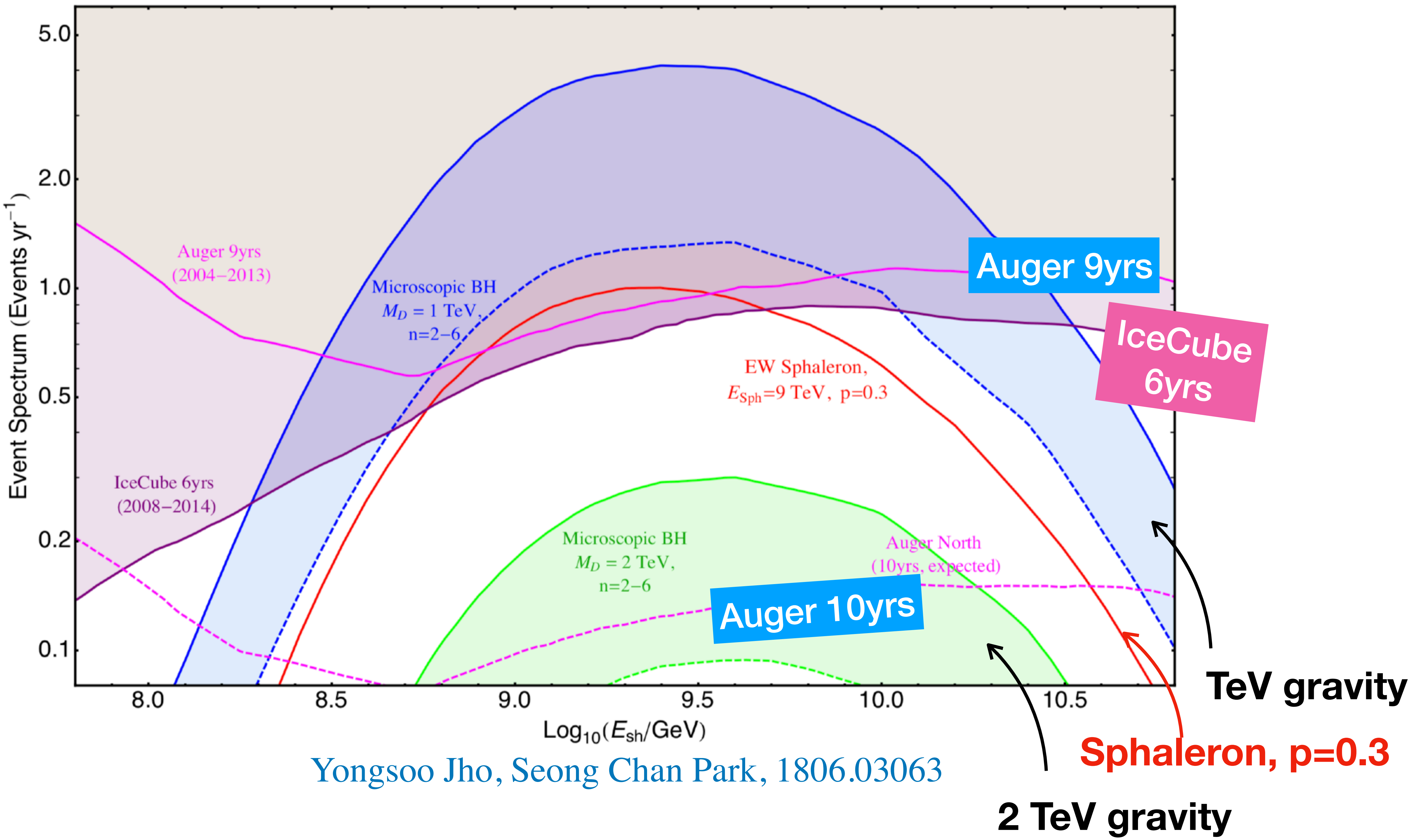
Event rate spectrum



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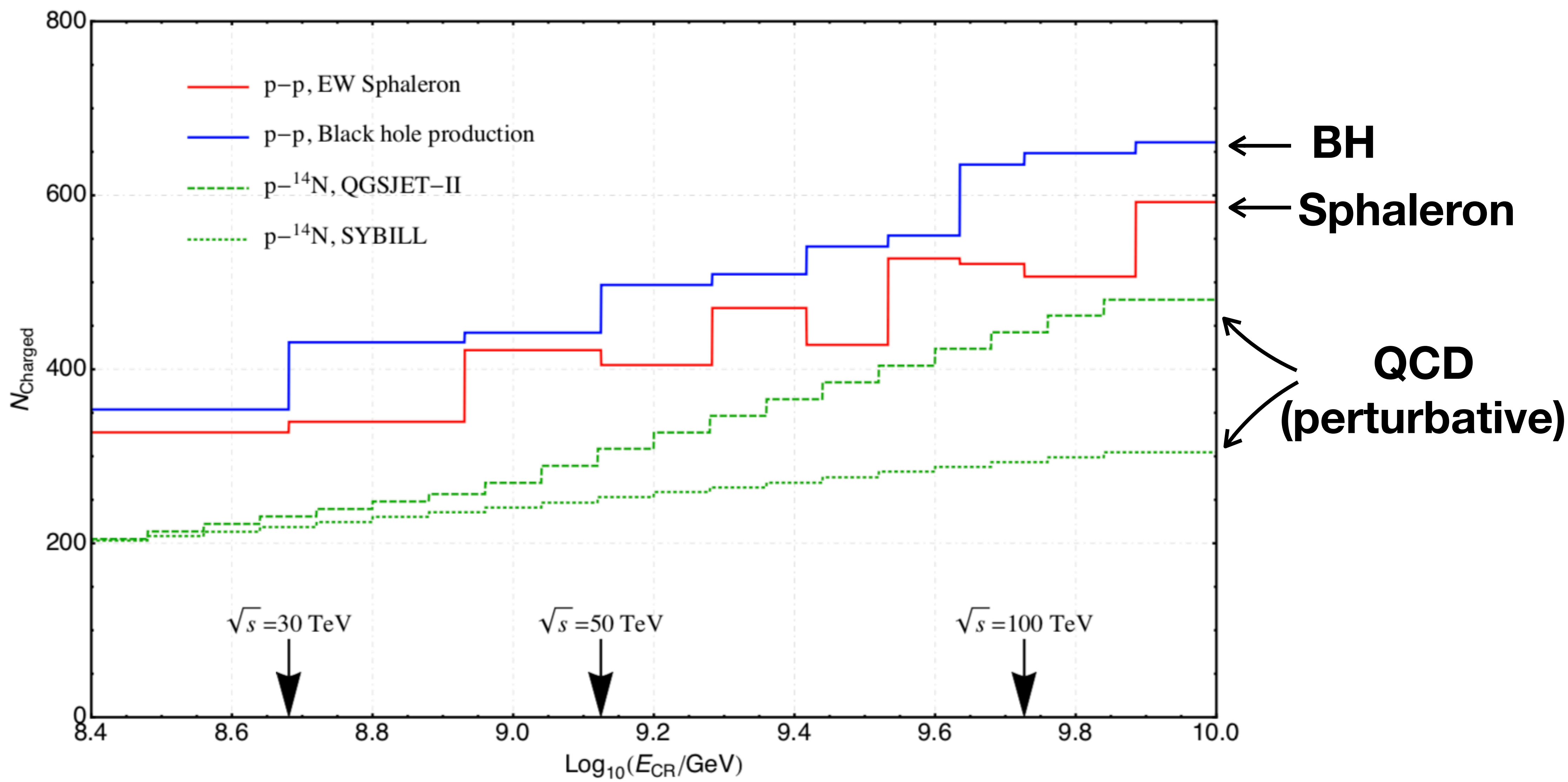
Features of NP events (i)
:Larger charged particle multiplicity



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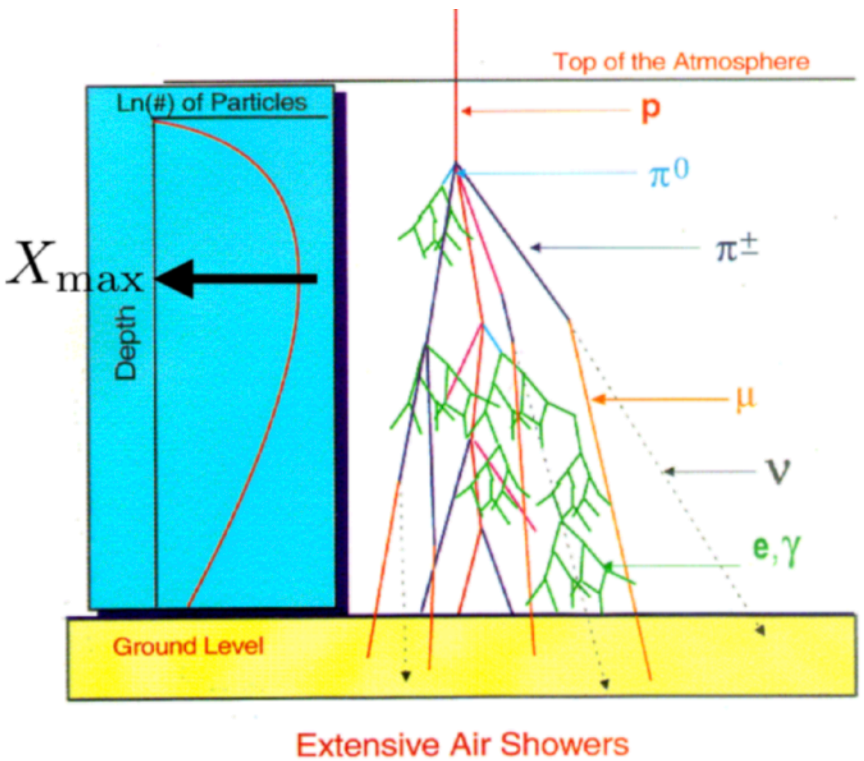
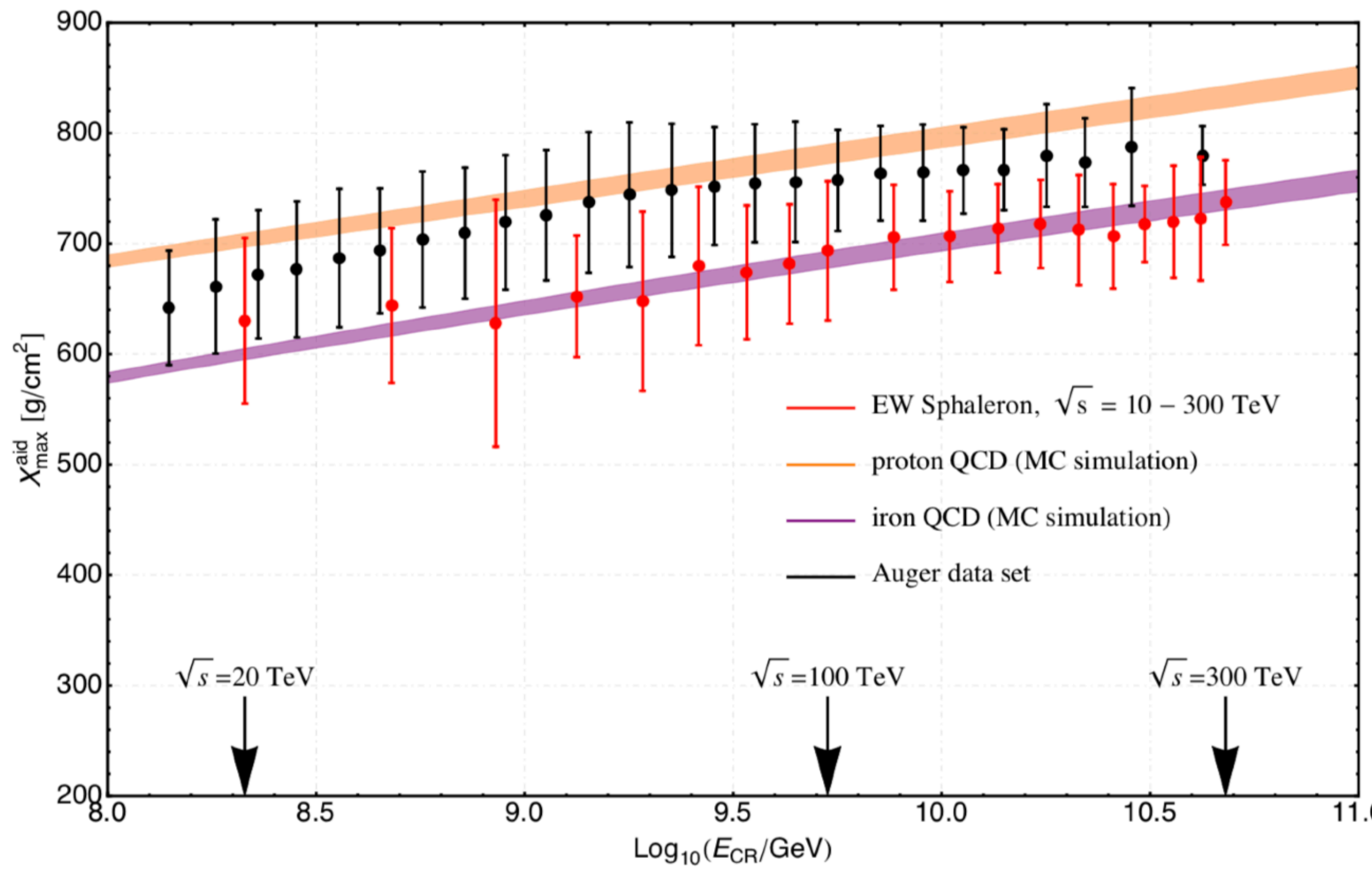
Features of NP events (ii) :quicker longitudinal development



Longitudinal development of air-shower can be observed by the fluorescence light detector (FD) (in the range of 300-430 nm)



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Features of NP events (iii) :broader distribution of the 'X_0'

probability distribution of the primary interaction point

CR-N cross section

primary interaction point

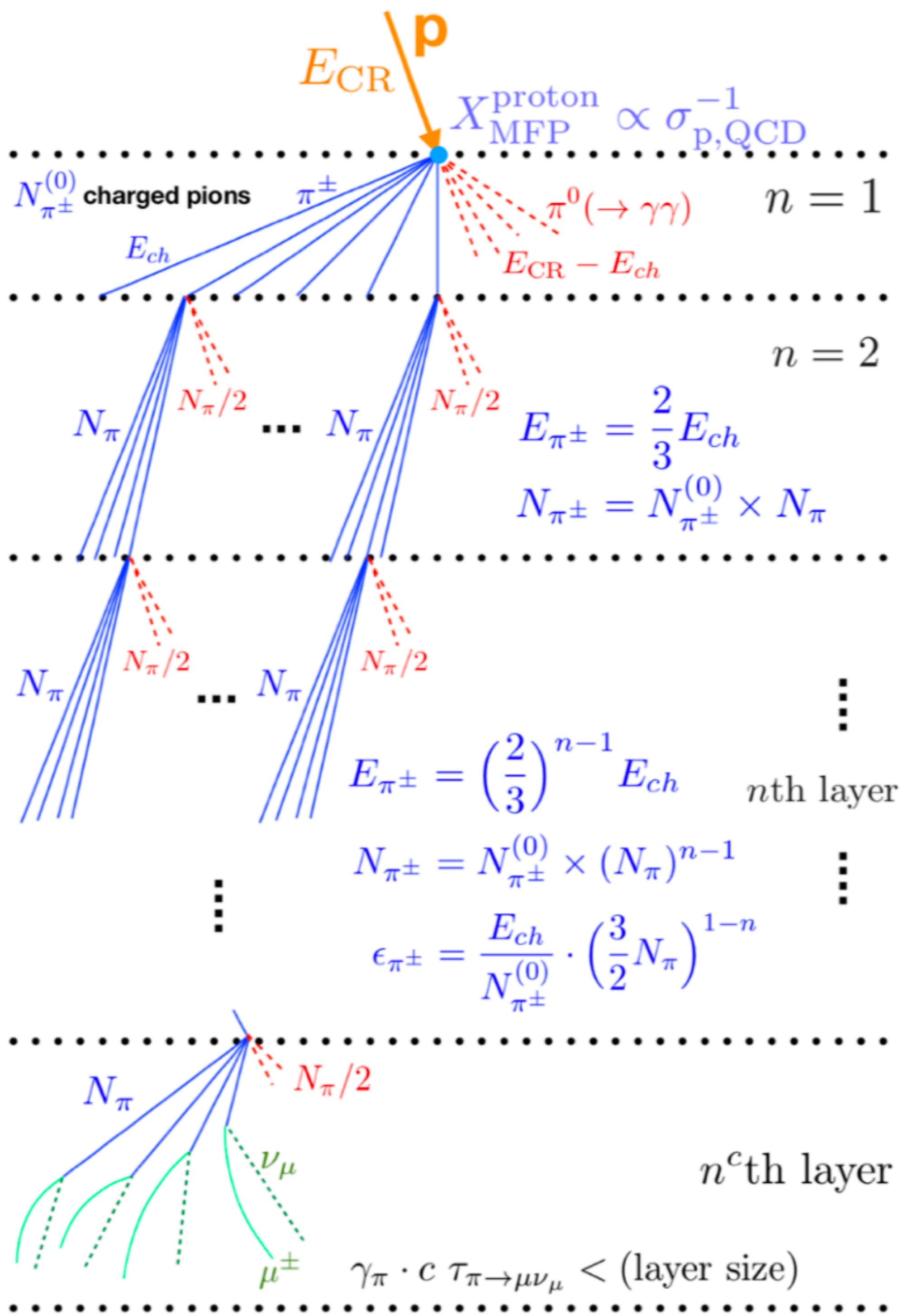
$$P(X_0) \propto \exp\left(-\sigma_{\mathrm{int}} N_A A_{\mathrm{atm}}^{-1} X_0\right)$$

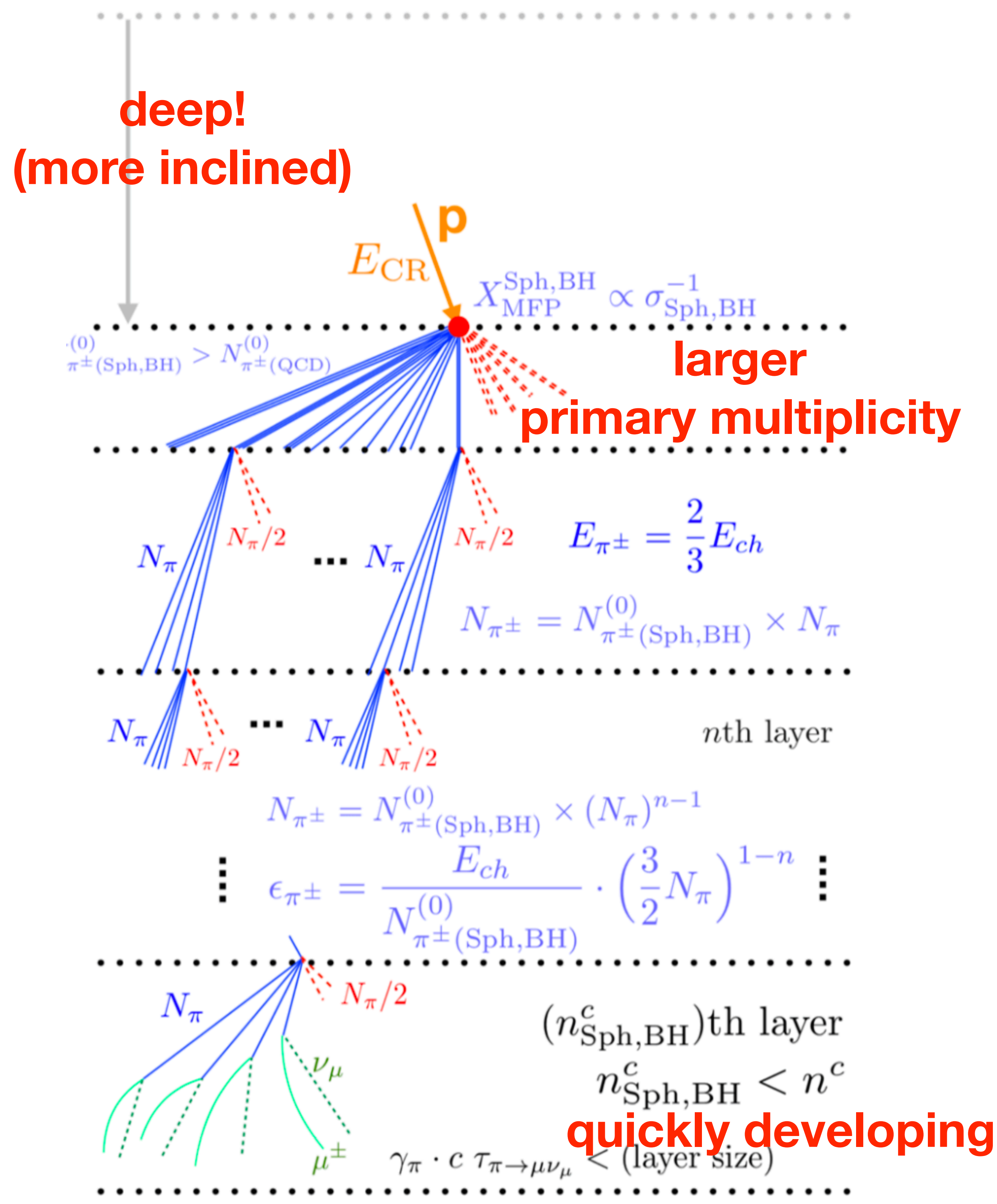
Avogadro number

average Atomic mass of atm ~14

$\sigma_{QCD} > \sigma_{NP}$ **=> NP distribution is broader**

p, QCD vs p, Sph or BH





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Summary

- UHECRs provide ‘very interesting’ chances of probing NP beyond 10 TeV

- We showed that ‘EW sphaleron’ and ‘Microscopic Blackholes’ are within the reach of future coming observation at Pierre Auger / TA (and IceCube too! stay tuned)

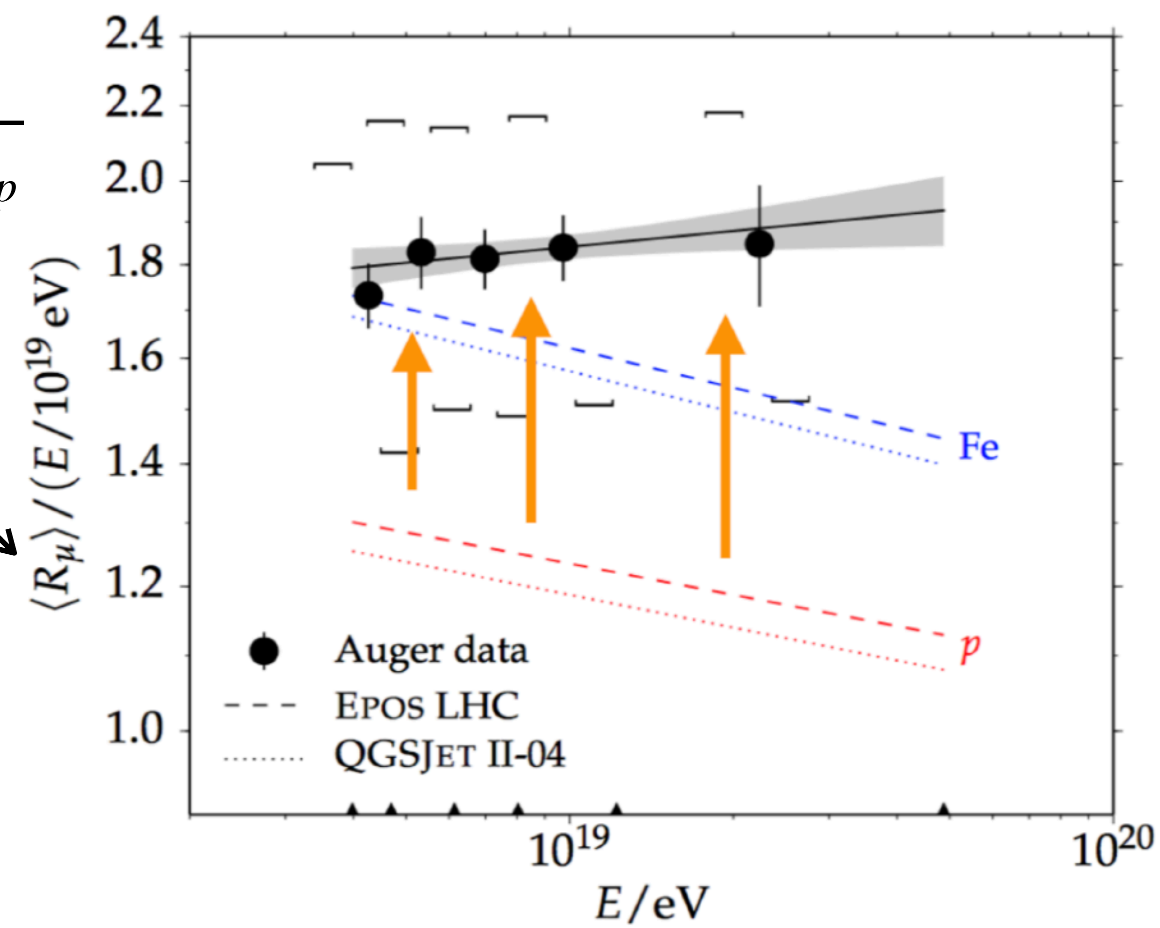
- NP features can be tested by extensive air shower with high multiplicity, more inclined (or deeper), rapidly developing, having broader X_0 distribution of interaction points.

(bonus) muon excess

$$R_\mu = \frac{N_\mu}{N_{exp}}$$

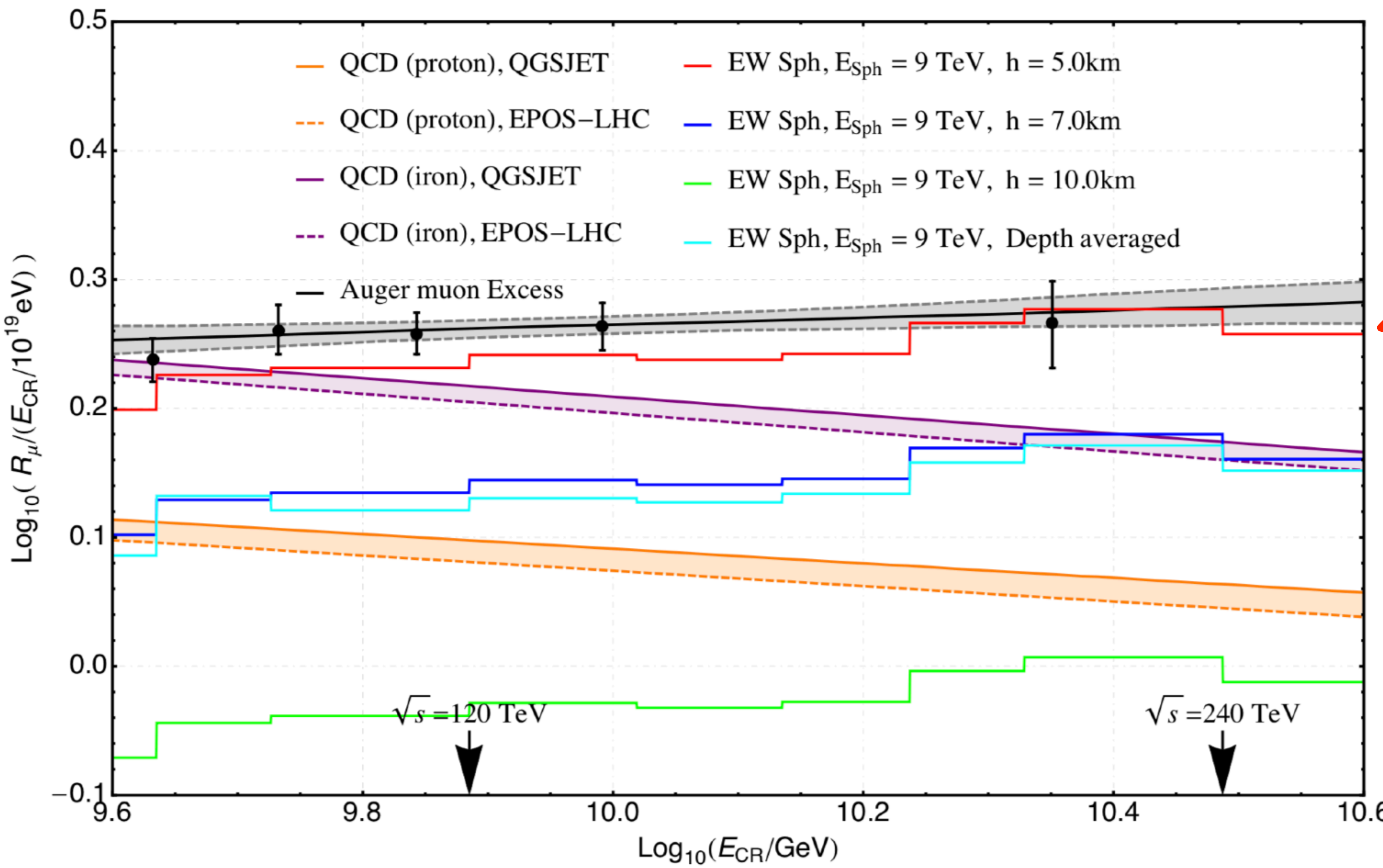
- Auger 9-yrs data suggests that there are ‘muon excess events’ having a larger number of muons compared to the expected.

$$\langle R_\mu \rangle = \int_0^{X_{max}} P(X, \sigma_{int}) R_\mu(X) dX$$



[Pierre Auger collaboration, PRD91(2015) no.3, 032003]

NP explanation?



Highly deep air-showers may contribute to the muon excess.

(not very plausible)